Solid state amplifiers for PIP-II

Mahendra Lad (SPC 650 MHz RF Power)

RRCAT ,Indore (DAE), INDIA

(On behalf of SSPA Development teams at BARC,Mumbai & RRCAT,Indore,India)

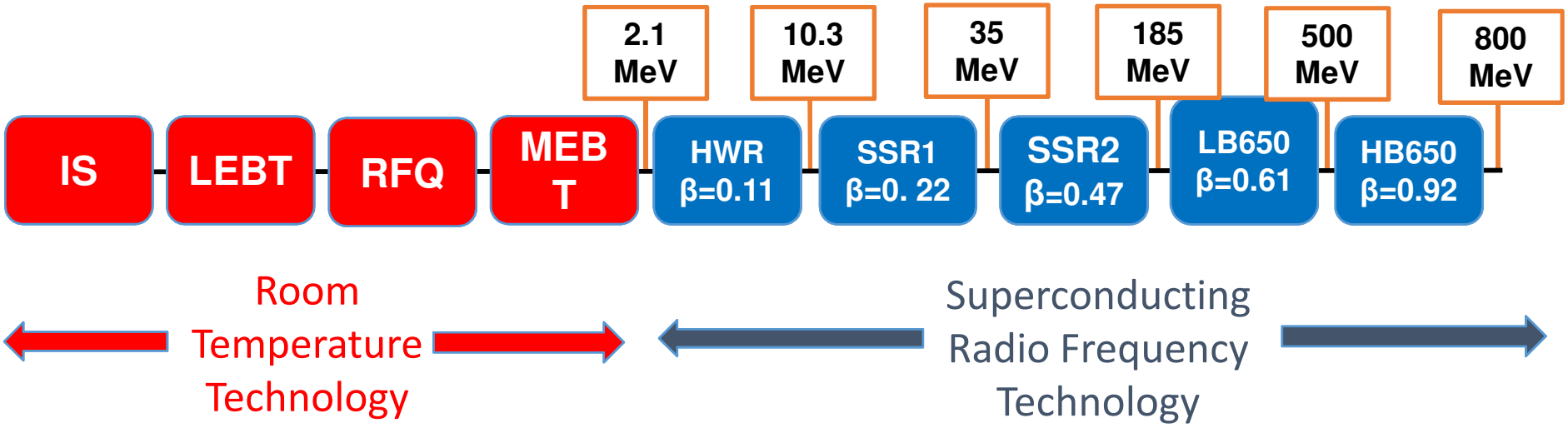
A few words about me

- “Joined RRCAT, Indore, India (DAE) in 1987 as Scientific Officer
- Working since last 34 plus years at RRCAT , to work on development of solid state (60 kW*4 -CW), Klystron (12 MW pulsed,60 kW*4-CW), IOT (60kW*1-CW) based high Power RF systems, LLRF controls and associated RF technologies like high power NC RF cavities, RF circulators, DC power supplies for RF amplifiers, high power coaxial transmission line components like DC, Combiners, RF loads and RF substrates etc.
- Positions held as LLRF Lab head, RF controls Section head, RF Systems division head, presently Associate director for Proton Accelerator Group at RRCAT
- More than 30 yrs experience in accelerator R&D projects and RF operations
  - Managed construction and commissioning of Indus RF systems, extensive knowledge and experience in design, development, commissioning and interfacing accelerator RF.
- Worked at Synchrotron Trieste, ELETTRA for 3 months and as Guest Scientist for 7 months at Synchrotron ,ANKA, Karlsruhe ,Germany

Outline

- Solid State RF Amplifiers (SSPA) for PIP-II Project-Overview
- Technical Progress towards development of SSPA
- Summary

The PIP-II 800 MeV Linac



Courtesey: Lia Merminga,FNAL USA

RF power requirement for PIP II

Section	Qty*	Freq (MHz)	Power (kW)	Phase	Source
RFQ	2	162.5	75	R&D	FNAL
Buncher	4	162.5	3	R&D	FNAL
First HWR	1	162.5	3	R&D	FNAL
Other HWR	7	162.5	7	R&D	FNAL
SSR1	8	325	7	R&D	DAE
SSR1	8	325	7	Construction	DAE
SSR2	5	325	20	R&D	DAE
SSR2	30	325	20	Construction	DAE
LB650	8	650	40	R&D	DAE
LB650	25	650	40	Construction	DAE
HB650	24	650	70	Construction	DAE

Room Temperature Cavities

Supercon-ducting Cavities

DAE Deliverables

Courtesy: Jim Steimel ,FNAL USA

Development of SSPA :DAE institutes (BARC, Mumbai,RRCAT,Indore INDIA)

Under Indian Institutions Fermi lab Collaboration (IIFC) development of SSPA at 325 MHz, for SSR1 &SSR2 (by BARC, Mumbai) and at 650 MHz for LB & HB SC cavities (by RRCAT, Indore ,India) are taken up. The work includes design,fabrication, testing and delivery of the RF power amplifiers as in kind contributions.

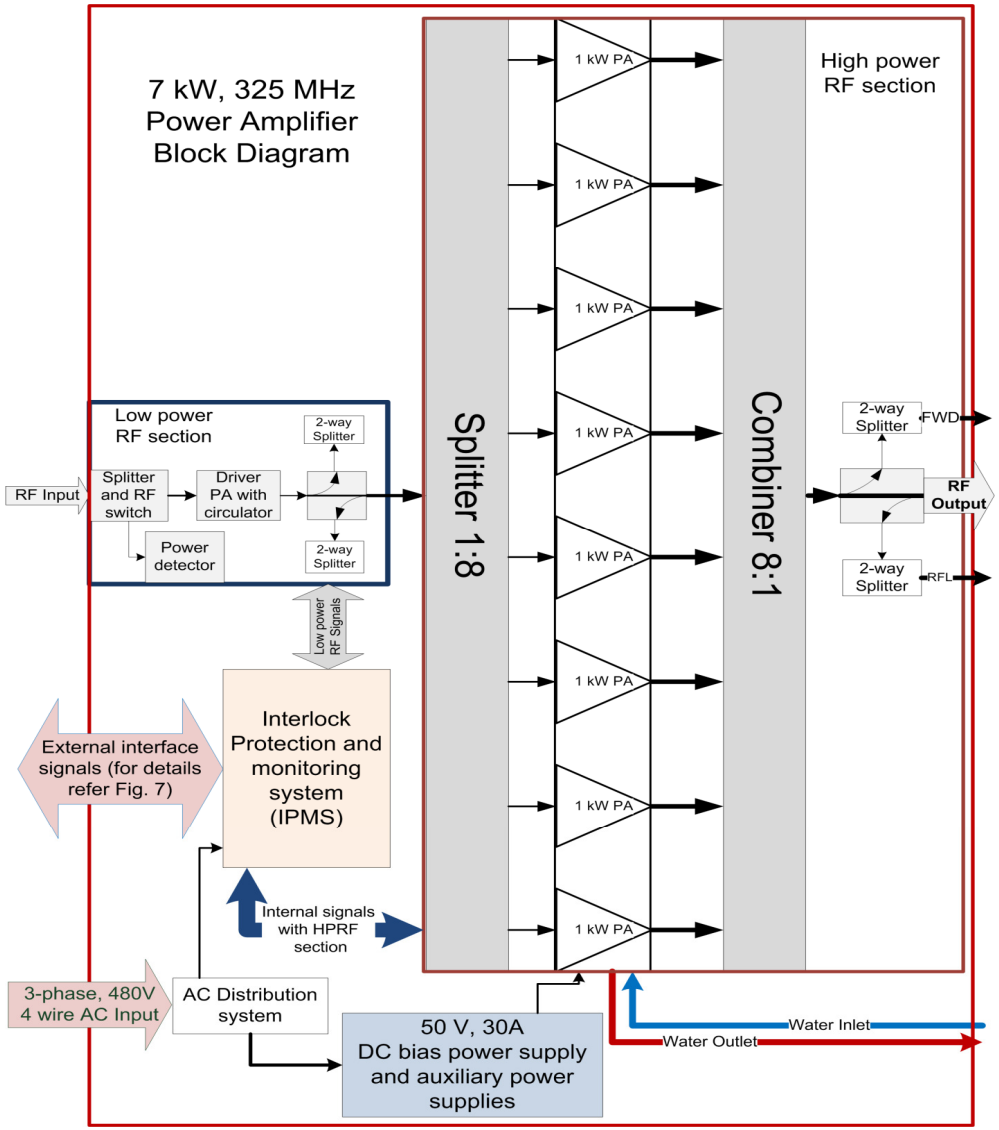
Choice of Solid State RF Amplifier

- Primarily due to non availability of vacuum tube from sources and with modest RF power requirement in SC RF cavity RF system in accelerators ,SSPA are better choice.
- Further with high power RF LD MOSFET available and increasing use of solid state amplifiers contributing towards improvement in performance and reduction in cost; SSPA are obvious choice due to due to the fact that the solid state high power amplifiers offer many advantages like
- **Modularity,**
- **Graceful degradation**
- **No high voltage requirement**
- **Low maintenance.**

In SSPA due to modest RF power devices available , common configuration for high power SSPAs are modules with individual high power transistors have their outputs summed for final high power specification up to few 100s of kW.

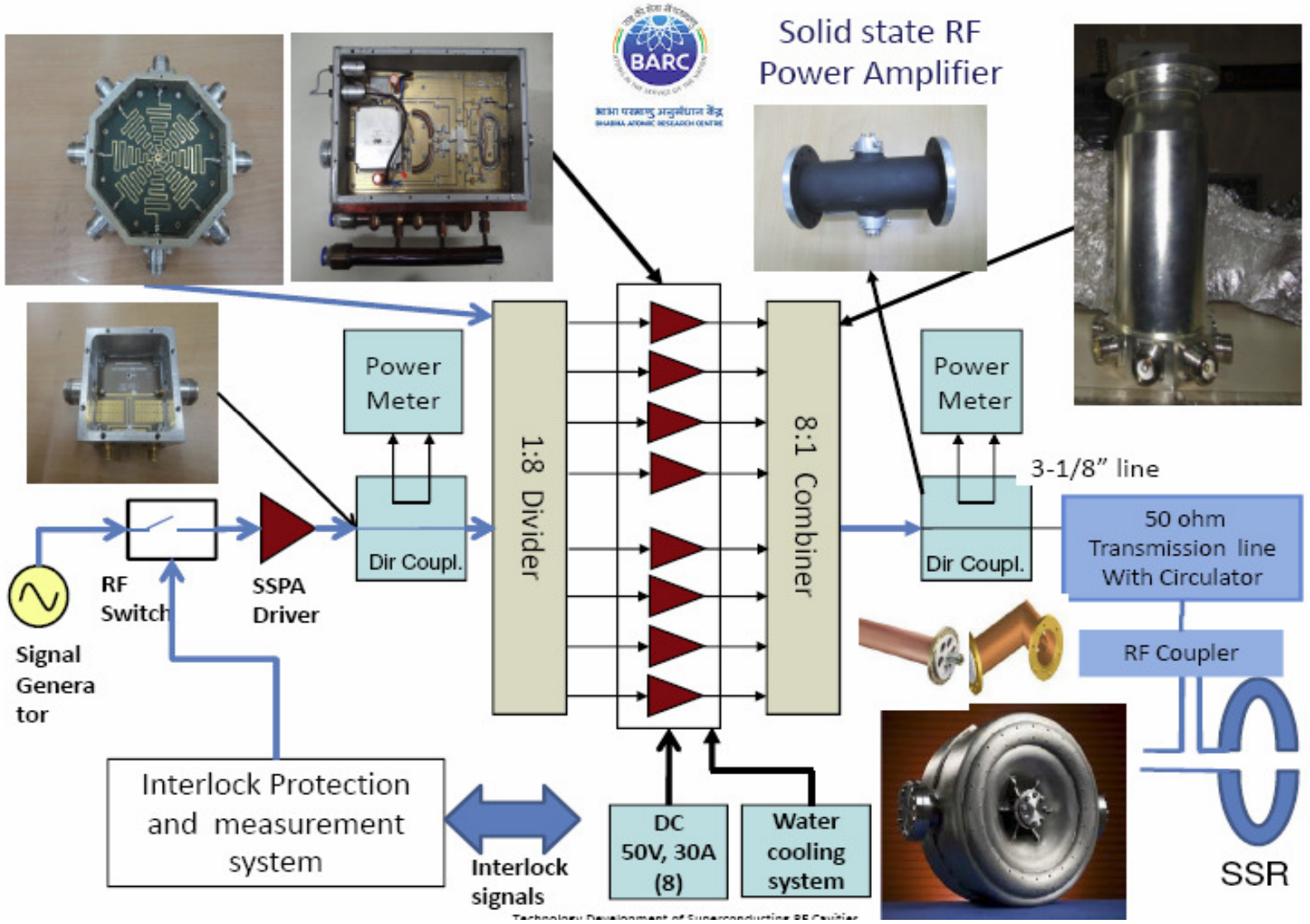
Development of 325 MHz SSPA : (BARC, Mumbai, INDIA)

- Under IIFC ,BARC, India is involved in design and development of 7kW & 20kW SSPA at 325 MHz for coupling RF power to single spoke resonator (SSR) - a superconducting accelerator module for PIP-II .
- The amplifiers are designed with with high Efficienc(~70%) and high power gain 1kW RF modules.
- Bandwidth high enough to support microsecond rise times for pulsed operation.
- The assumed plan for 20kW units is combining more modules.



Courtesy: Manjiri Pande,BARC,Mumbai India

Development of 325 MHz SSPA : (BARC, Mumbai, INDIA)



Courtesy: Manjiri Pande,BARC,Mumbai India

325 MHz SSPA contd….

Currently 8 of BARC's amplifiers are connected to SSR1

Curtsey Victor Grzelak, HPRF,FNAL USA

PIP-II SSA controls meeting – PIP2IT Status

Currently 8 of BARC's amplifiers are connected to SSR1

Curtsey Victor Grzelak, HPRF,FNAL USA

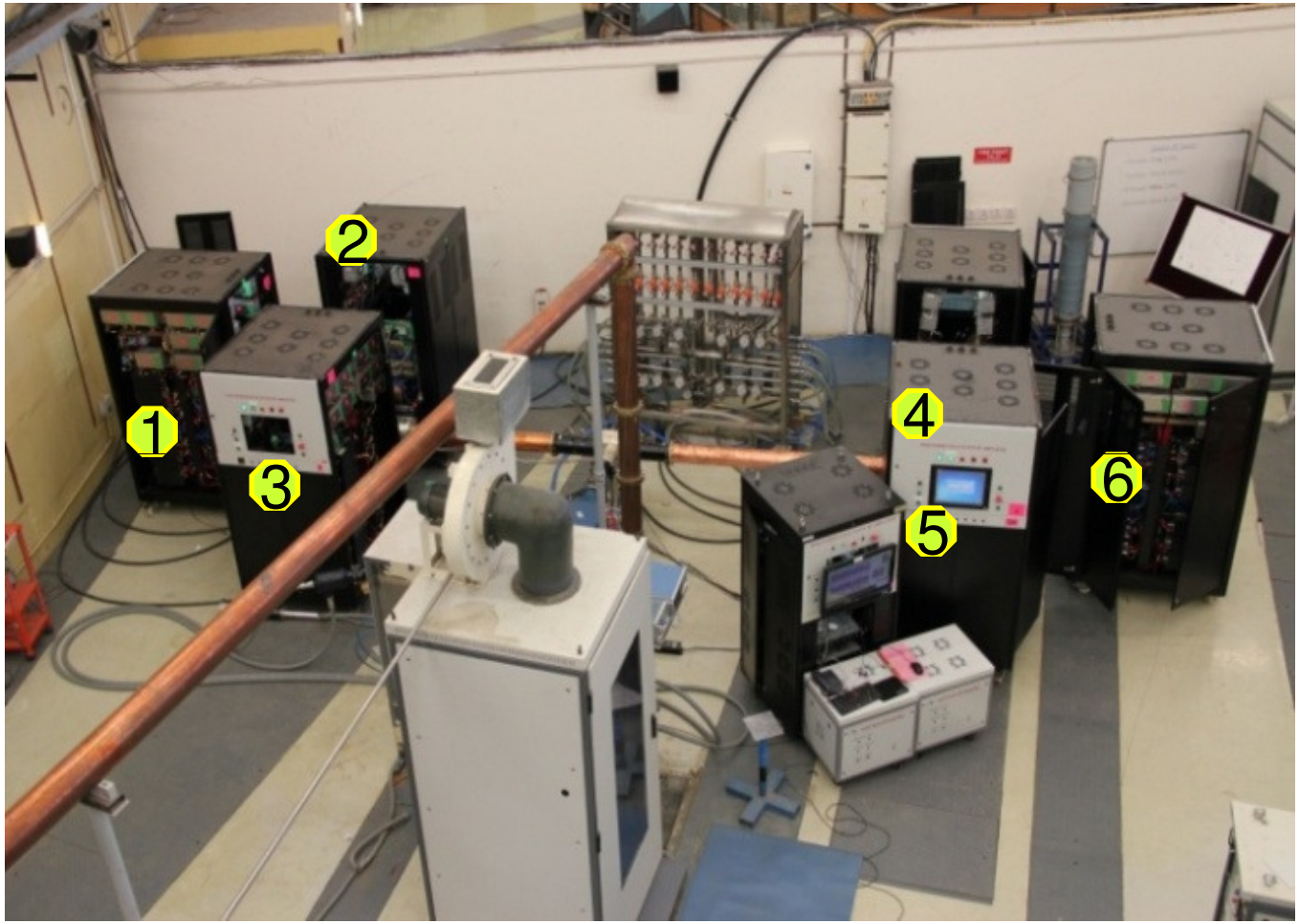
Solid State RF Amplifier development expertise at RRCAT

- At RRCAT, Indore India the team had been engaged in Solid State RF Amplifier development as following.
  - 31.613 MHz (2 kW CW SSPA, for electron SRS Indus-1) ,
  - 505.8 MHz (Total 240 kW CW, with four RF stations of 60 kW each for electron SRS Indus-2) these were commissioned and are running in round the clock operation mode for beam line users since 2011
  - Also at 2856 MHz (pulsed 1 kW,2 kW & 4 kW) for electron LINAC,IRFEL microwave systems)

505.8 MHz SSPA

31.6 MHz SSPA

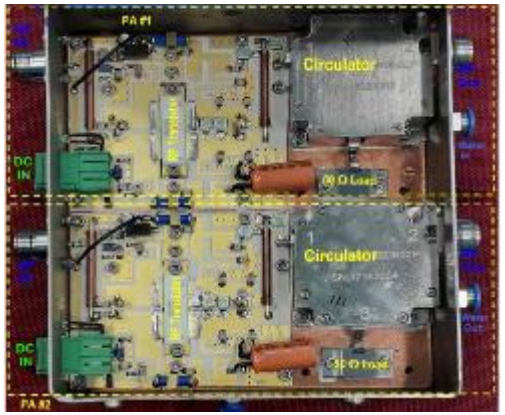
505.8 MHz Solid State RF Amplifier for electron SRS,Indus-2



One 60 kW, 505.8 MHz RF station ,the work published in Rev. of Sci. Instru. Journal 2014.

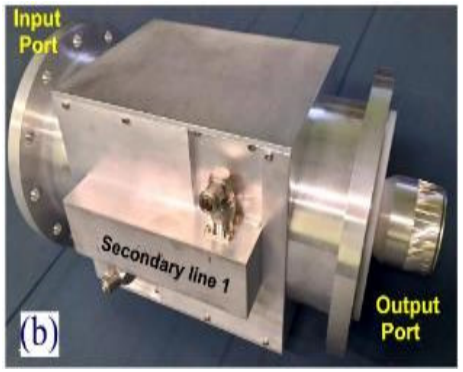
Main RF Components of 650 MHz Solid State RF Amplifier

1. **Rigid Coaxial RF Components** Directional couplers, divider, combiner, mounting hardware etc. -1 set
2. **Power Amplifier (PA) Module** with water cooled enclosures, RF components and RF connectors (one PA module consists of four gain block) – 26 sets
3. **Amplifier Cabinet/Unit** wired and assembled with 3 phase electrical system, DC bias supplies, water headers, water tubes, PT 100 temperature measurement hardware, front panel hardware – 2 sets
4. **Embedded SSRFA control subsystem** including FPGA Controller, digital, analog input, output modules, RF Detectors, Industrial PC, directional sensors etc. – 2 sets

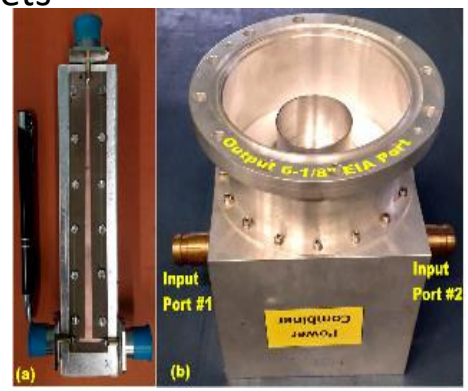


2 kW (4X500W) PA assembly

RF Power Sensor



Directional coupler with 6-⅛″ ports



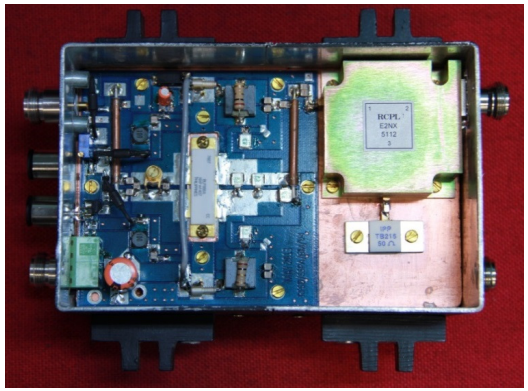
Fabricated 2-port (a) tapered microstrip divider (b) High power combiner with 6-⅛″ input and output ports.

Four of these developed technologies have been suitably transferred to private vendor through TTCD BARC.

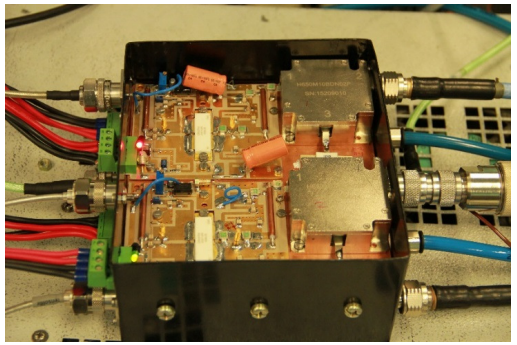
Development of 650 MHz SSPA : (RRCAT, Indore , INDIA)

Status summary 650 MHz SSPA

- Initially under R&D phase requirement of 30 kW SSPA was there and a prototype SSPA RF amplifier designed with 64 RF power modules of 500 W (shown below fig a) was fabricated and tested in 2014-15.
- In Nov 2015 requirement of 650 MHz RF amplifier was changed from 30 kW to 40 kW, the RF amplifier was redesigned with similar 96 RF power modules of 500 W mounted on racks of same form factor and modified with new RF components and modules. In 2017-18,SSPA was tested with 1 dB RF power of 32 kW. One such prototype unit of 650 MHz SSPA (R&D phase) was sent to FANL in Feb 2021; the amplifier is installed, commissioned and tested. One similar RF amplifier of R&D phase is installed, commissioned and tested at HTS-2 (RRCAT) for testing 650 MHz SC RF cavity.
- To meet 40 kW,1dB compression point output power, new RF amplifier was designed in April 2020 with 128 RF power modules of 500 W. The new design has compact 2kW RF cold plate housing four modules of 500 W(fig b)



500W X 2 power module at 650 MHz



500W X 4 power module at 650 MHz

Design Changes from 30 kW to 40 kW Power in 650 MHz SSRFA

Compact design was explored in order to accommodate 48+2=50 PA modules in a euro rack compared to 32 PA modules, used in 15kW unit of 30 kW SSRFA

500W PA Modules

Compact 48 port design explored in order to get 20 kW power from a single rack instead of using three 15 kW units

Power divider and combiner

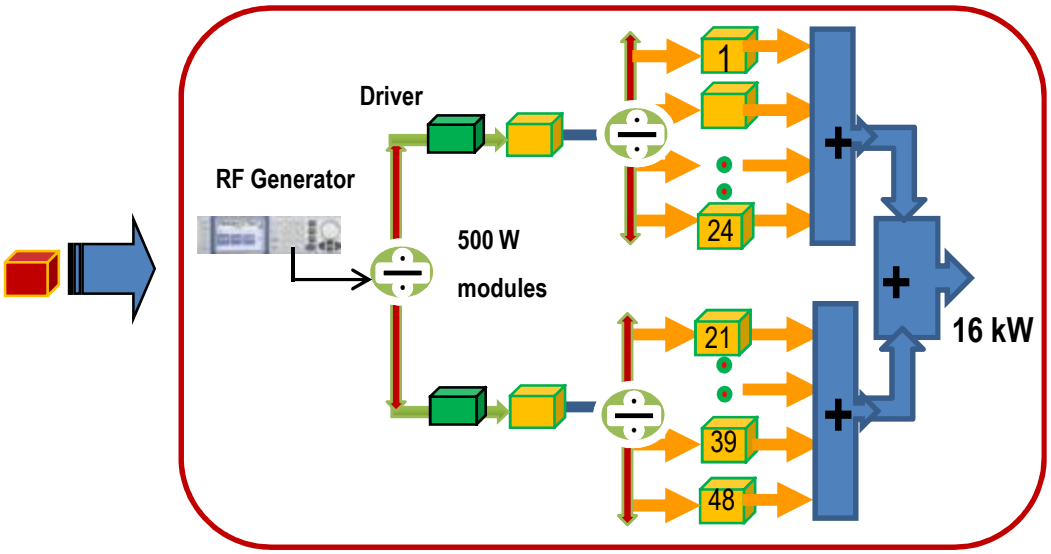
Euro rack design was completely reviewed to accommodate 48 PA modules and also 48 SMPS, as compared to earlier design using 32 modules. Water circuit was also modified.

Enclosure for 20 kW unit

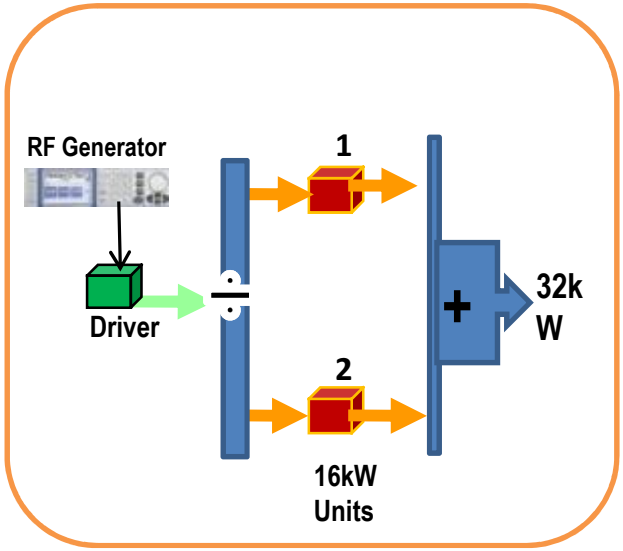
In order to incorporate functional requirement and to control two units in master-slave made, major changes were done by incorporating microcontroller based control boards in new 40kW SSRFA.

Distributed Embedded data acquisition

Scheme for 650 MHz 32 kW RF Power Source



16 kW Unit scheme used in 32kW Amplifier



32kW Amplifier Scheme

- Proposed scheme for 32kW solid state amplifier -
  - 32kW power will be obtained by summing output of two 16 kW units.
  - Each 16 kW unit will be housed in a single euro rack with 48 amplifier modules, each one using LDMOS giving output RF power of 500 W.

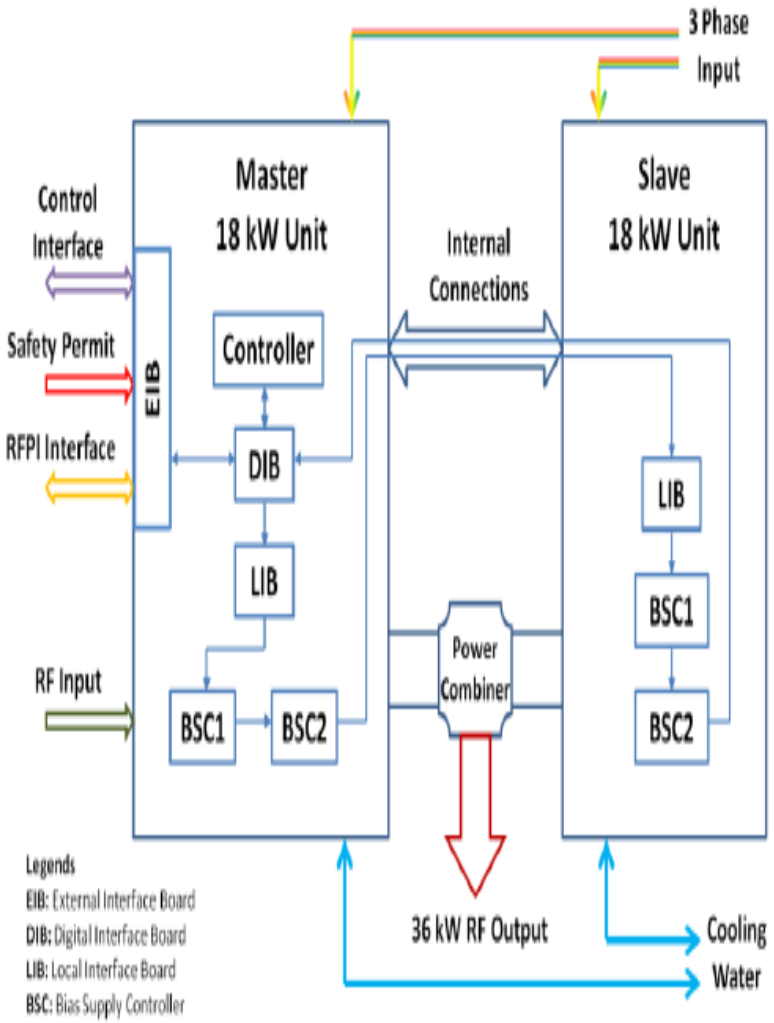
Control System Scheme

For data acquisition, each 16 kW unit together with its interlocks form an self contained system with its own embedded control operations performed by a graphical code developed in-house using LabVIEW™ RT and FPGA.

All of the PAs, with the help of 1 kW coupler provide rectified sample of forward and reflected power to cRIO controller (from National Instruments™) through RS485 networks connected on its 4-port module.

The whole system works as a distributed system over TCP/IP network where two 16 kW units function as master and slave respectively, and they are centrally coordinated by a master controller and interfaced with a PC running a LabVIEW based HMI application.

Different Control Interface Boards

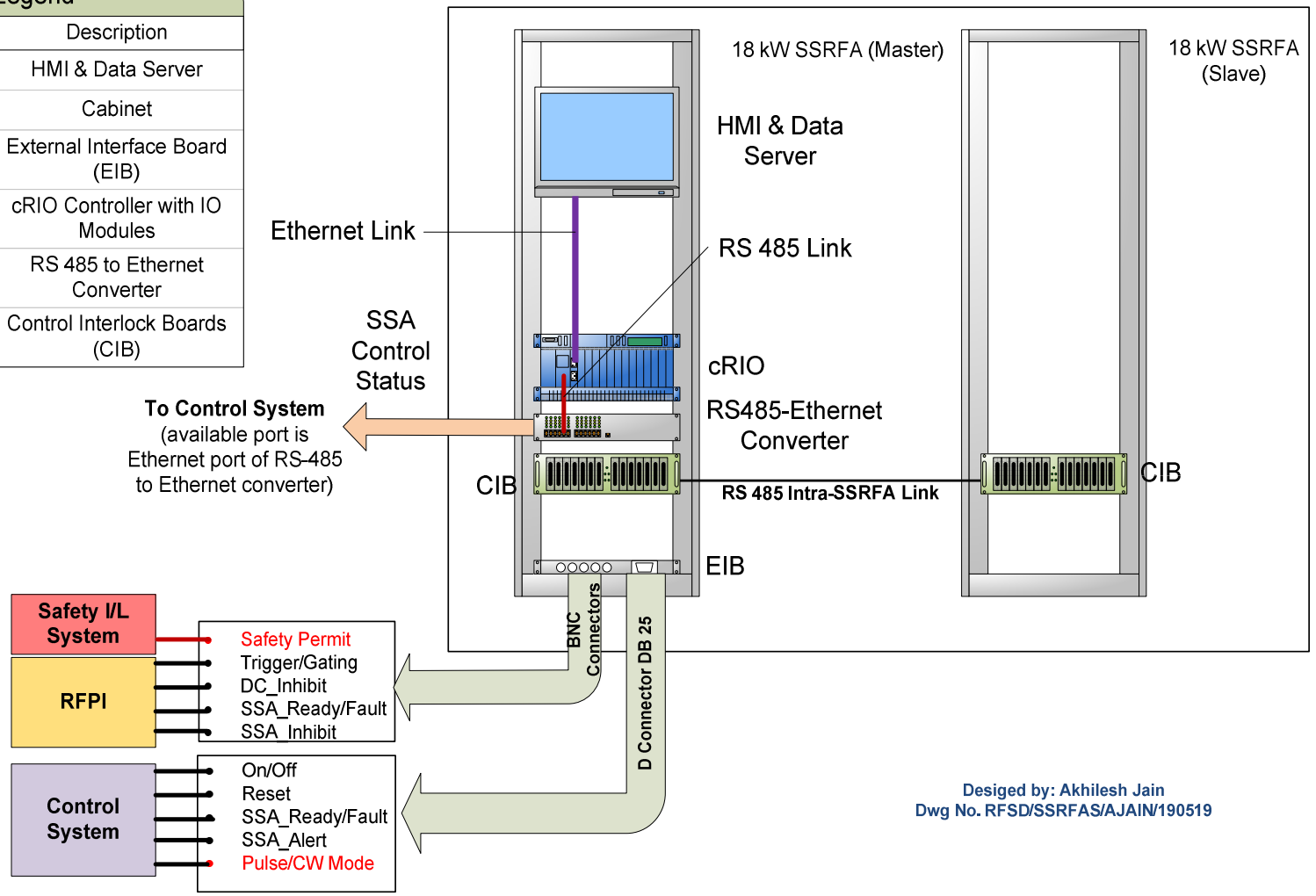


Sr. No.	Name	Function
1	Local Interface board (LIB)	It accepts all control/interlock signals of the rack/unit.
2	External interface board (EIB)	It is responsible for external/remote communication on RS 485 bus. It is part of only master unit.
3	Bias Supply Controller (BSC)	It controls ON/OFF sequence of 3 phase contactor.
4	Microcontroller unit (MCU)	It is core unit of all control/interlock boards except Digital interface board and Temperature input board.
5	Front panel controller (FPC)	It is local human interface for complete unit.
6	Digital interface board (DIB)	It is interface between input/output signals from of the cRIO controller. It also communicates with FPC. It does not have embedded Microcontroller unit.

For data acquisition, each 650 MHz unit is equipped with Control Interface Boards. Embedded control operations are performed by a graphical code developed in-house using LabVIEW™ RT and FPGA.

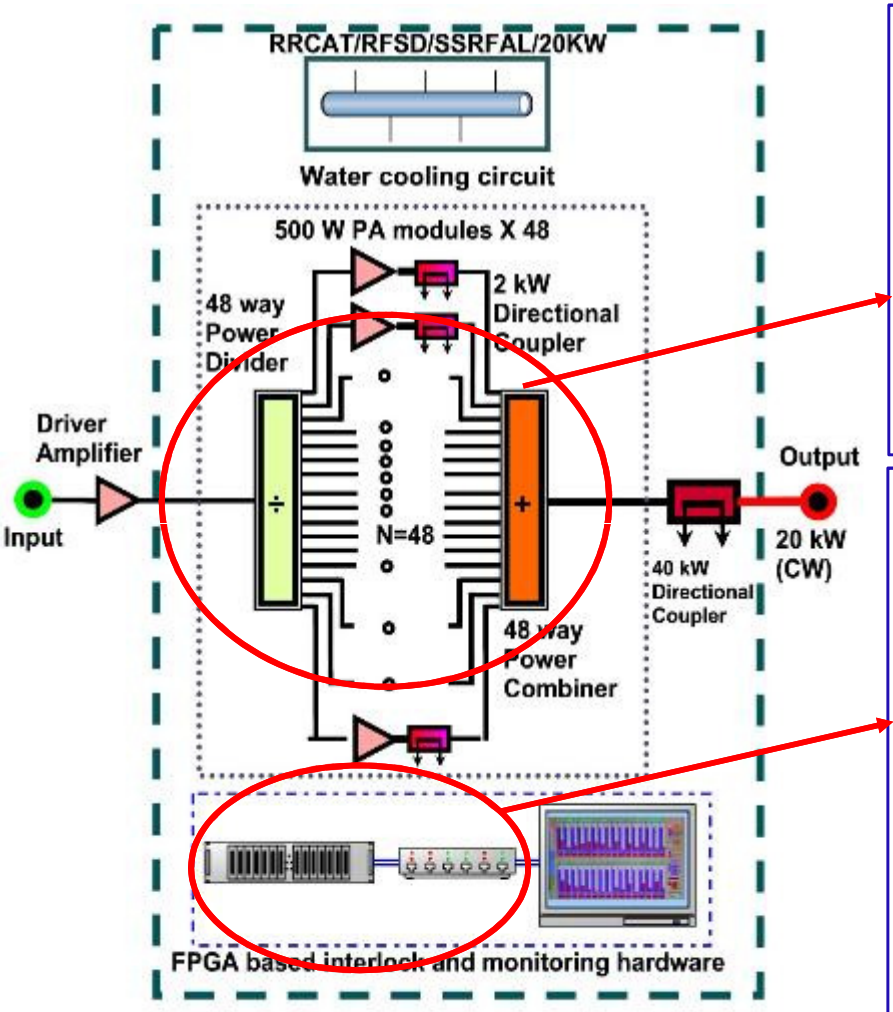
Designed Control/Interlock Scheme for 650 MHz SSRFA

Legend		
Symbol	Count	Description
	1	HMI & Data Server
	2	Cabinet
	1	External Interface Board (EIB)
	1	cRIO Controller with IO Modules
	1	RS 485 to Ethernet Converter
	2	Control Interlock Boards (CIB)



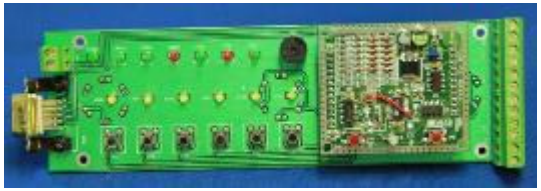
Low power amplifier and control/interlock hardware is different in both units, all other details are same for both master and slave units.

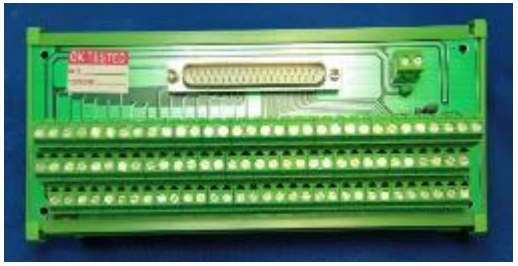
650 MHz, 32 kW Solid state RF Amplifier: Major Sub systems

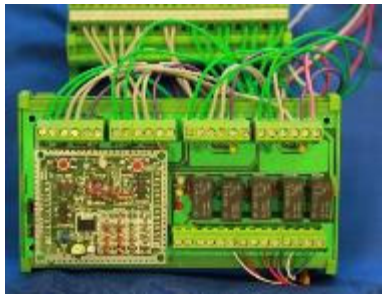


Designed architecture of 20 kW Amplifier

48 way Power Divider (left) and Combiner (20 kW power handling)

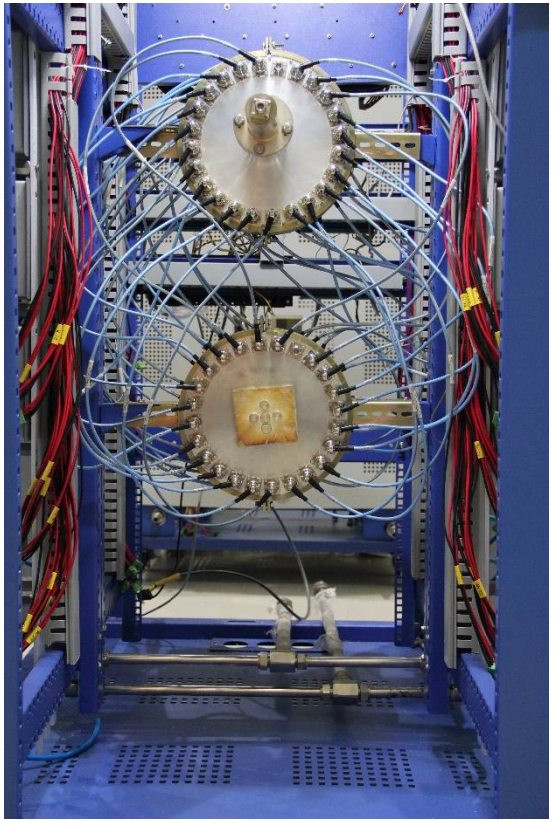






New Data Acquisition Boards, designed to meet modified technical requirements of new FRS.

650 MHz, 32 kW Solid state RF Amplifier: Major Sub systems

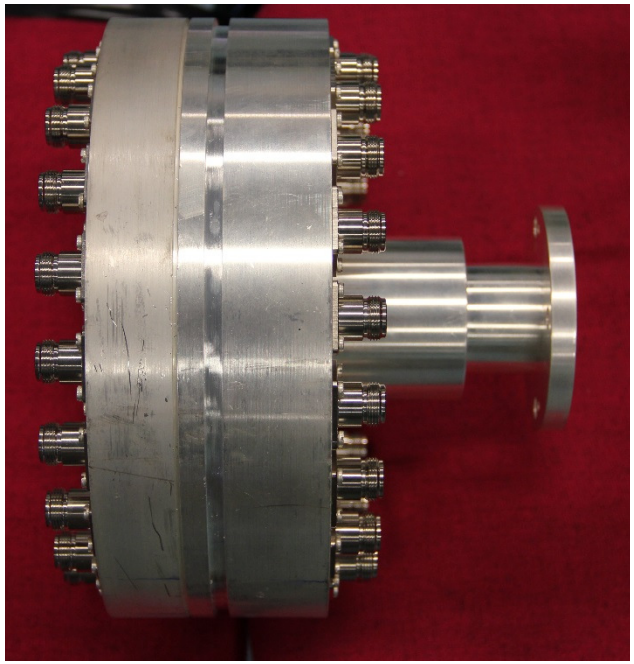


48 way Power divider and combiner

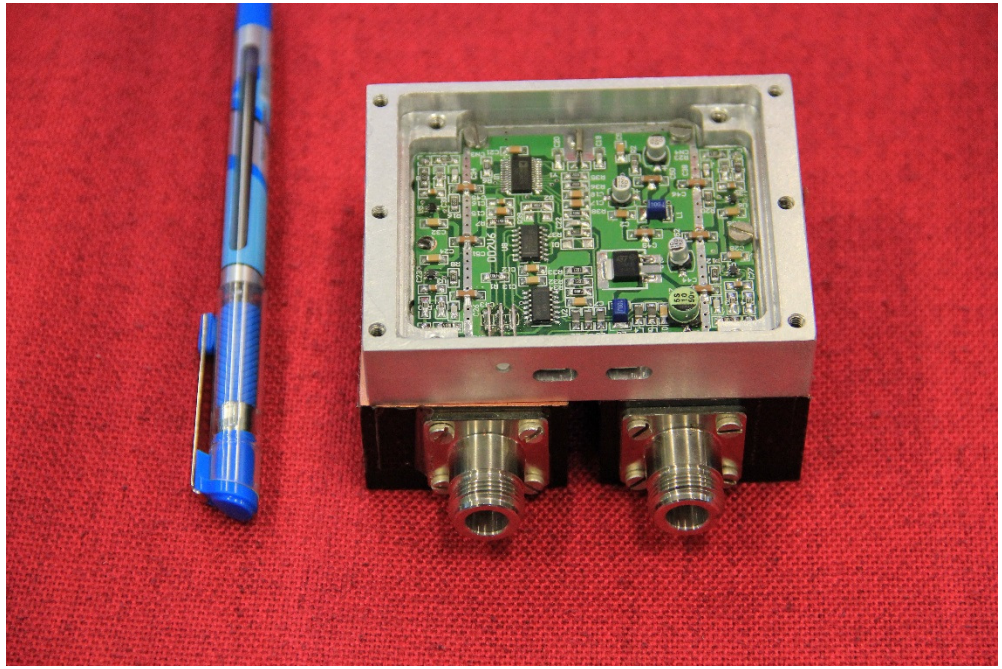
Electrical and embedded control sub systems

Combiner/Splitter & Digital Detector

48 way RF Splitter and 48 way high power RF Combiner are used in each rack and 24 nos. of DD for measuring Fwd. and Refl. RF power of two PA modules ,it provides RF power and thermal trip as it is mounted on same heat sink as PA.



48 way Power divider & combiner

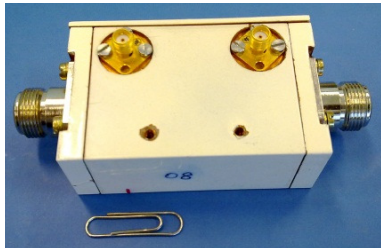


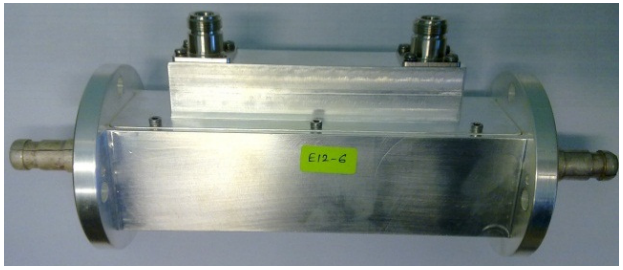
Digital Detector

High power Directional couplers

Directional couplers are required in multiple in order to measure RF signal. The present design is with rigid structure for main line as well as auxiliary line.

Type	Max. forward power	Coupling factor	Main line connectors	Minimum directivity	Minimum return loss
Low power design	1 kW CW	40 dB	N type	30 dB	25 dB
Medium power design	5 kW CW	50 dB	1-5/8" EIA	28 dB	25 dB
High power dual coupling design	20 kW CW	50 dB	3-1/8" EIA	28 dB	25 dB
High power dual coupling design	65 kW CW	50 dB	6-1/8" EIA	26 dB	23 dB

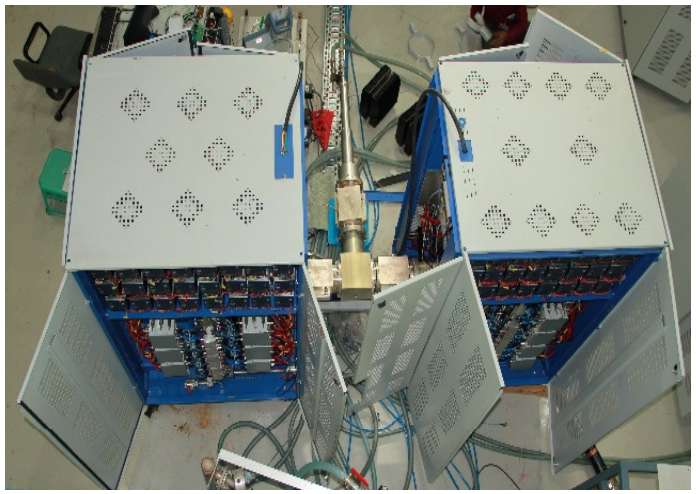




Designed 1 kW, 5 kW and 20 kW directional couplers

Successful Test of 650 MHz, 32 kW Amplifier Prototype

- Testing of 650 MHz, 32 kW amplifier was completed at RRCAT on May 3, 2019.Testing confirmed all operational parameters required for R&D phase of PIP-II project.



650 MHz, 32 kW Amplifier acceptance testing at RRCAT

R&D phase 650 MHz RF amplifier (left) installed at FNAL and (right) results during test of SSPA up to 32 kW

32 kW 650 MHz SSPA installed at HTS

HTS Cave

High power test set up for testing superconducting RF cavities

Design and Development of 40 kW 650 MHz CW solid state RF amplifier

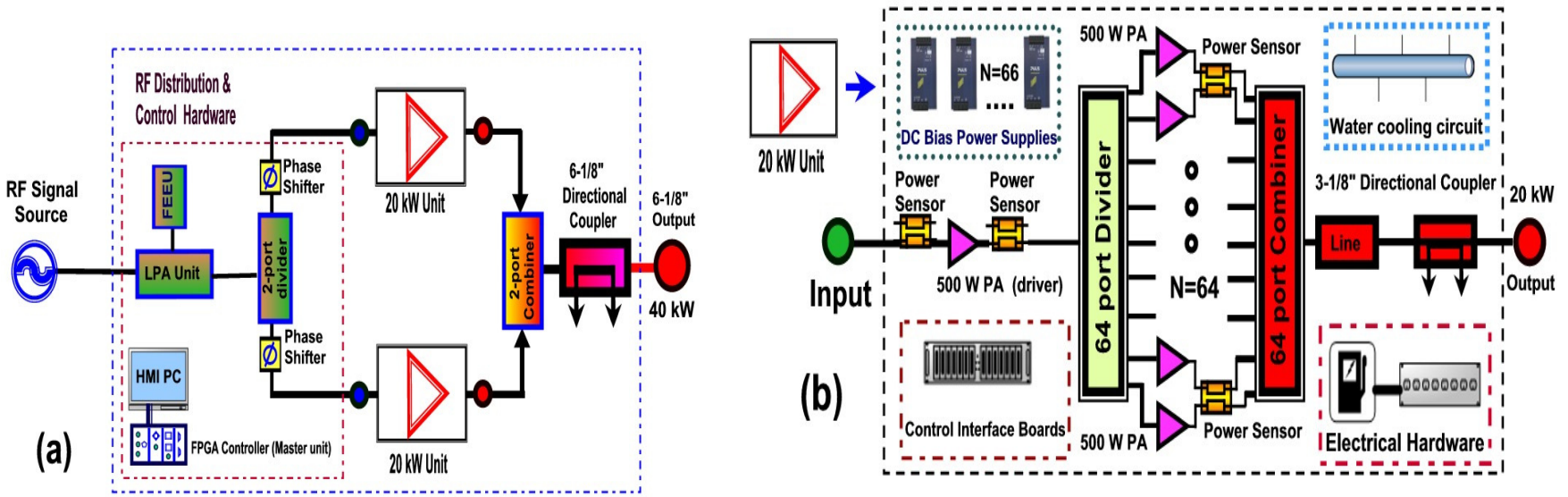
- With similar architecture used for 32 kW SSPA, a prototype 40 kW 650 MHz Solid State RF Amplifier was designed with 128 RF power modules ,as per TRS finalized with FNAL,USA.
- It has two custom designed amplifier cabinets of 20 kW each RF power combines with high power two way combiner
- 128 numbers of 500 W RF amplifier modules along with DC power supply modules, control/interlock cards, directional sensors, 64 port dividers & 64 port combiner and 40 kW two way combiner.
- Prototype unit fabricated in two euro racks of sizes 1.2m*1.0m*2.0 m ,was tested in 2021 at full RF power of 40 kW with 50 ohms water cooled dummy load.
- The same unit was shipped in six big boxes,to FNAL,USA in Dec 2021.
- The 40 kW SSPA is under assembly at FNAL,USA .

PARAMETER	Value
RF output power	40 kW CW
Bandwidth @ 1 dB	±2 MHz
Power gain	> 85 dB
Bias voltage	48 V DC
Harmonics response	-30 dBc Max, tested within 2 GHz bandwidth
Spurious response	-50 dBc Max including power supply modulation, tested within 2 GHz bandwidth
AC input	3 phase 440V, 50 Hz
Physical dimensions	4.4 m x 2.2 m x 2 m (H)

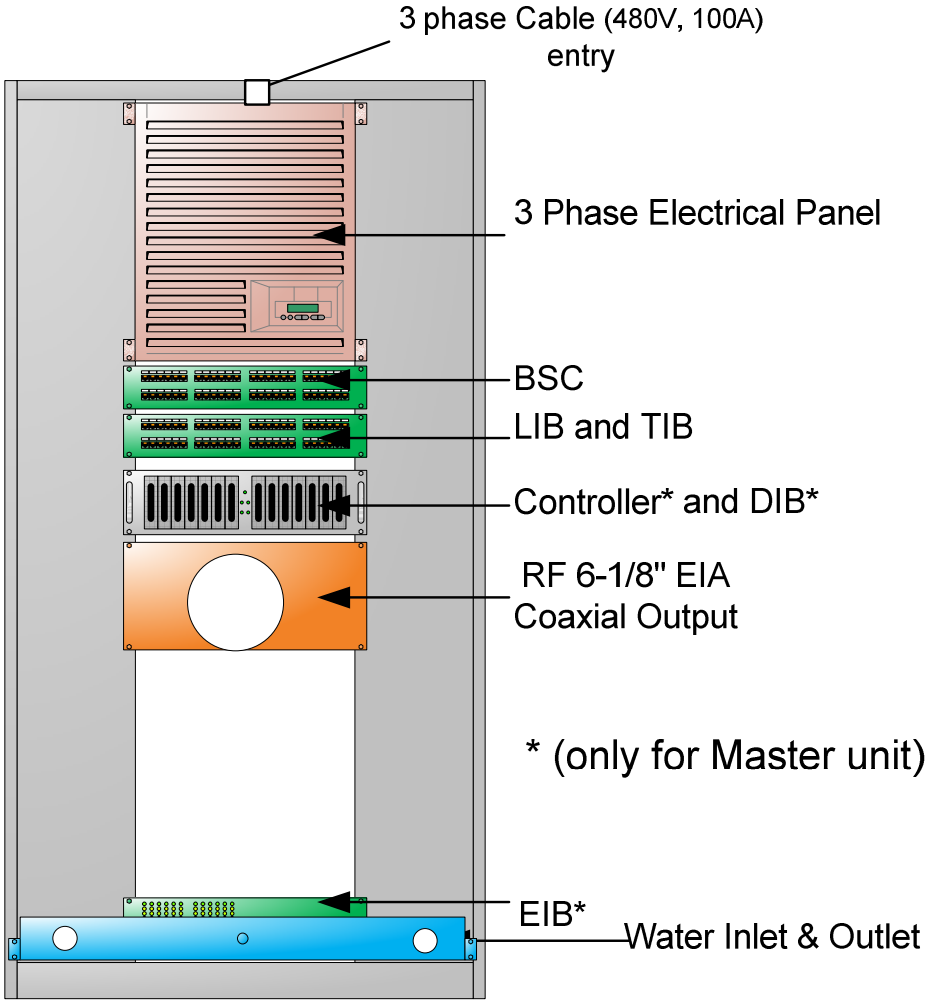
Development of 40 kW 650 MHz SSPA contd….

40 kW level Solid State RF Amplifier (SSRFA) was designed with two units of 20 kW, each one using 34 power amplifier (PA) cold plates, 132 SMPS, 66 sensors, 2 sets of 64 port radial dividers and combiners, 2 phase shifters, one two-port combiner, 2 high power line sections, and 3 high power directional couplers. All these components in desired quantity were fabricated and tested rigorously, before final assembly. The complete RF amplifier was fully assembled and RF tested up to 40 kW.

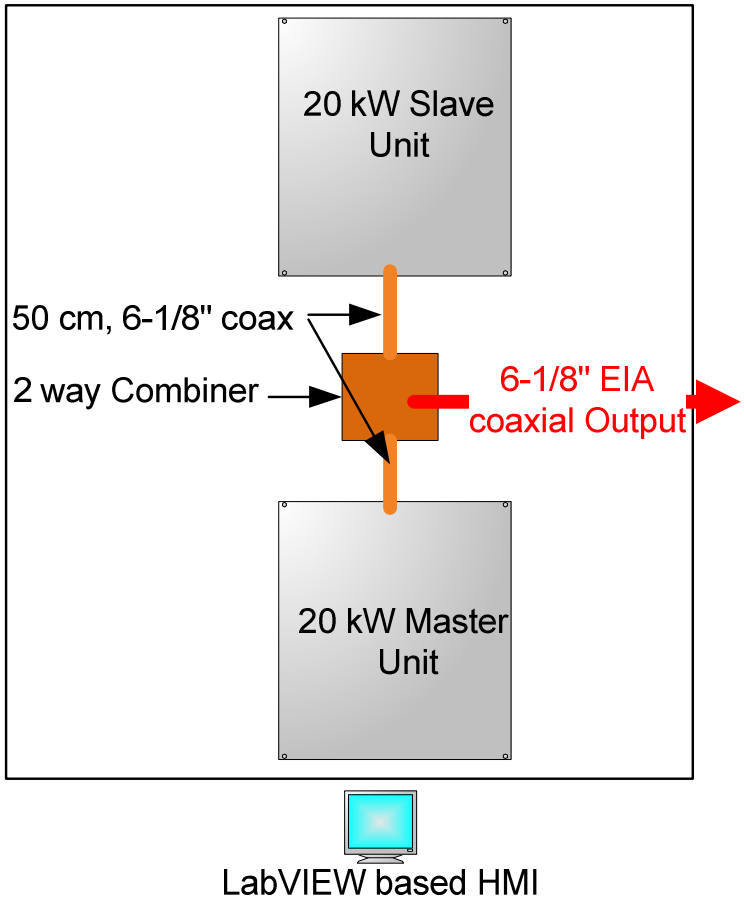
System Architecture



Scheme of 20kW units and their assembly



Rear view of 20 kW master/slave unit



Top view of 40 kW SSRFA

Development of 40 kW 650 MHz SSPA contd….

Under Indian Institution Fermilab collaboration (IIFC), the development of 40kW, 650 MHz Solid State Amplifiers is done at RRCAT, Indore, India as R&D phase deliverables.

Parameters	Values
Centre Frequency	650MHz
Pulsed/CW operation	CW and Pulse
RF Power Gain	> 75 dB
Power output at 1dB compression point	≥ 40kW
3 dB Bandwidth	± 2 MHz
AC Input Power	3 Phase 440-480 V AC
Output connection	6 1/8” EIA flange or WR1150
Input connection	N Type
Input impedance	50 ohm

TEST RESULTS of 40 kW 650 MHz SSPA

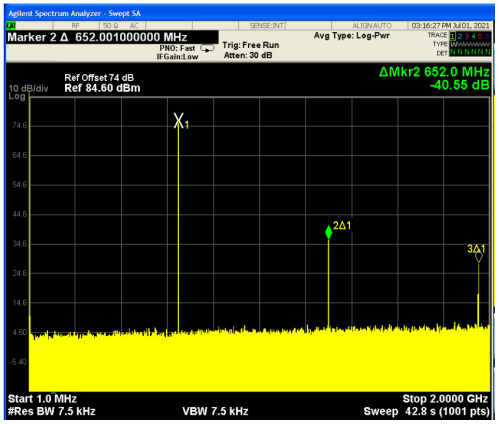
HARMONIC AND SPURIOUS MEASUREMENT

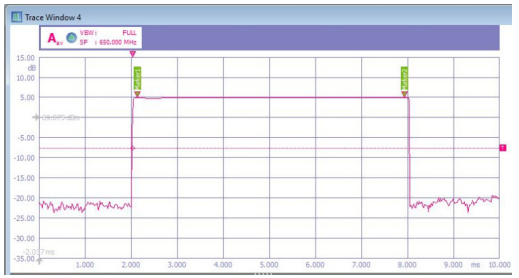
Span : 1 MHz to 2 GHz, RBW : 7.5 kHz, O/P Power : 40 kW

Second Harmonic : better than 40 dBc

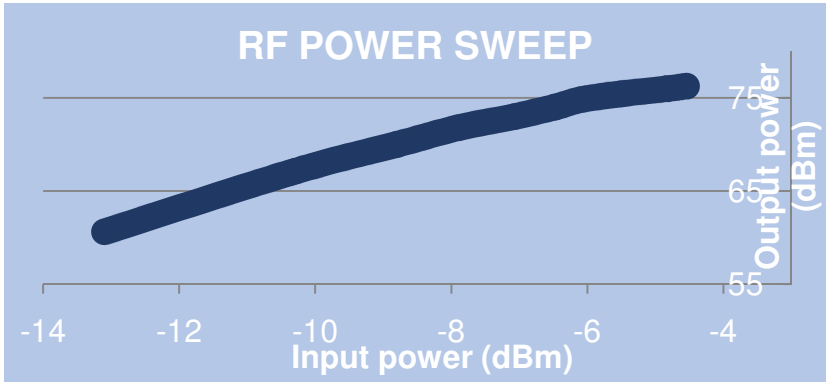
Third Harmonic : better than 49 dBc

Spurious : -68 dBc @ 1.25 GHz wrt 650 MHz





Snapshots of different measurements



Relevant Publication List

[1] Akhilesh Jain, D. K. Sharma, A. K. Gupta and M. Lad, "A 150 kW Pulse Solid State Amplifier for Radio Frequency Quadrupole Application," in *IEEE Transactions on Nuclear Science*, doi: 10.1109/TNS.2020.3025382, Sep 2020.

[2] D. K. Sharma, Akhilesh Jain, K. Pathak and M. Lad, "Compact dual-channel radio frequency power sensor for solid state amplifiers," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,, vol. 944, 2019.

[3] Akhilesh Jain, A. K. Gupta, D. K. Sharma, P. R. Hannurkar and S. Pathak, "Design and analysis of a high-power radial multi-way combiner," International Journal of Microwave and Wireless Technologies, vol. 6, no. 1, pp. 83-91, 2014.

[4] Akhilesh Jain, D. K. Sharma, A. K. Gupta, M. Lad, P. R. Hannurkar and S. K. Pathak, "System efficiency analysis for high power solid state radio frequency transmitter," Review of Scientific Instruments, vol. 65, no. 024707, pp. 1-8, 2014.

[5] Akhilesh Jain, "Advanced harmonically tuned radio frequency power amplifiers," RRCAT Newsletter, vol. 31, no. 2, pp. 42-50, Dec 2018.

[6] A. K. Gupta, Akhilesh Jain and M. Lad, "Design and development of 150 kW pulsed RF rigid coaxial line based 3-Way RF Power Combiner at 325 MHz," in Indian Particle Accelerator Conference, InPAC-19, New Delhi, 2019.

[7] Akhilesh Jain, P. R. Hannurkar, D. K. Sharma, A. K. Gupta, A. K. Tiwari, R. Kumar, M. Lad, P. D. Gupta and S. K. Pathak, "Design and Characterization of 50 kW Solid-State RF Amplifier," International Journal of Microwave and Wireless Technologies, vol. 6, no. 1, pp. 83-91, 2012.

Development of SSPA :DAE institutes (BARC, Mumbai,RRCAT,Indore INDIA)

Under this activity in addition to developments following documents have been prepared

Functional Requirement Specifications

- ED0008023-RF Power Systems FRS
- ED0003408-325 MHz SOLID STATE 7kW AMPLIFIER, FRS
- ED0003669-325 MHz SOLID STATE 20 kW AMPLIFIER, FRS
- ED0003413-650 MHz SOLID STATE 40 kW AMPLIFIER, FRS
- ED0003680-650 MHz SOLID STATE 70 kW AMPLIFIER, FRS

Technical Requirement Specifications

- ED0004290-7 kW RF POWER AMPLIFIER, TRS - SSR1 325 MHz
- ED0005489-TRS 40 kW, 650 MHz Solid State RF Power Amplifier System

Technical Requirement Specifications for 20 kW325 MHz RF POWER AMPLIFIER for SSR2 & 70 kW, 650 MHz Solid State RF Power Amplifier for HB 650 is under preparation

Technical interface specification documents

- ED0006360 – 650 MHz 40kW RFPA Interface Control Document
- ED0006356 – 325 MHz 7 kW Solid State RFPA Interface Control Document
- Interface to Conventional Facilities contained in Room Data Sheets
- Technical Requirement Specifications

Development of SSPA :DAE institutes (BARC, Mumbai,RRCAT,Indore INDIA)

- Summary
- ***SSPA developments 7 kW at 325 MHz and 40 kW at 650 MHz by DAE institutes under R&D phase has been successfully accomplished.***
- ***9 units of 7 kW 325 MHz SSPA are delivered and 8 are installed at FNAL,USA.***
- ***Two 650 MHz SSPA one each of 32 kW and 40 kW are delivered to FNAL,USA ;32 kW is fully assembled and tested at FNAL and 40 kW is under final assembly.***
- ***TRS of 20 kW,325 MHZ and 40 kW ,650 MHz (with modified specifications) are finalized and prototype of each is under developments at DAE institutes..***

International partnerships are essential for the success of the PIP-II project.

Thank You